Hindawi
Advances in Materials Science and Engineering
Volume 2020, Article ID 5301968, 11 pages
https://doi.org/10.1155/2020/5301968

Research Article

Study on Water Absorption and Thermal Conductivity of Tunnel Insulation Materials in a Cold Region under Freeze-Thaw Conditions

Youyun Li,[1] Huan Wang ,[1] Li Yang,[1,2] and Shiqiang Su[1]

[1]*Key Laboratory of Special Area Highway Engineering, Ministry of Education, Chang'an University, Xi'an 710064, China*
[2]*Sichuan Expressway Construction and Development Group Co., Ltd., Chengdu 610000, Si'chuan, China*

Correspondence should be addressed to Huan Wang; 2018221089@chd.edu.cn

Received 29 April 2020; Revised 25 June 2020; Accepted 30 June 2020; Published 17 July 2020

Academic Editor: Guillaume Bernard-Granger

A thermal insulation layer is often deposited on the lining structure of tunnels in cold regions to solve the problem of frost damage. When the air humidity in the tunnel becomes excessively high, the thermal insulation material tends to absorb water, leading to significant changes in thermal conductivity. Moreover, the temperature differences between the day and night cycles have been observed to be significant in portal sections of cold region tunnels, which facilitate the freeze-thaw cycle and, consequently, deteriorate the performance of the thermal insulation material. Therefore, the purpose of this study is to determine the changes in the water absorption, thermal conductivity, and microstructure of polyurethane and polyphenolic insulation boards under freeze-thaw conditions. To this end, an indoor water absorption test was conducted for both the insulation boards till they were saturated, which then underwent a freeze-thaw cycle test. It was determined that the water absorption and thermal conductivities of these boards increased linearly with the number of freeze-thaw cycles. In order to explore the change of thermal conductivity of thermal insulation materials after moisture absorption, this study provides insights into the relationship between the thermal conductivities and water contents of tunnel insulation materials under normal and freezing temperatures.

1. Introduction

In order to promote the development of transportation in Western China, particularly the cold regions at high altitudes and latitudes, the number of tunnels being built has been augmented considerably [1–6]. Previous studies have determined that more than 80% of tunnels in the cold regions of China are impacted by different degrees of frost damage, of which about 60% are affected by leakage. The theory of "ten tunnels and nine leakages" reflects the universality and seriousness of the leakage problem [7–9]. Numerous reasons can be ascribed for the tunnel frost damage in cold areas; however, the primary reason has been determined to be the disturbances in the original temperature field of the surrounding rocks in the tunnel [10–12]. Temperature variations within the tunnel have been observed to facilitate the freezing and thawing of groundwater within the tunnel, which jeopardizes the stability of the lining structure. To reduce the influence of these temperature changes, a thermal insulation layer is deposited on the tunnel lining structure [13–15]. When choosing the thermal insulation material, the first consideration is the thermal conductivity of the material, which reflects the ability of the material to conduct heat.

The degree of the influence of moisture content on thermal conductivity will vary with the type of thermal insulation material, which, in turn, depends on the composition and internal structure of the material. This also has an influence on the water absorption performance and heat transfer mode of the thermal insulation material [16–19]. The variation in the thermal conductivity of the polyurethane insulation material with certain moisture content was researched by Abu-Jdayi et al. It was shown that an increase in the moisture content of polyurethane from 0% to 10%

corresponded to an increase in the thermal conductivity from 0.025 W/(m·K) to 0.046 W/(m·K) [20]. Loboda and Szurman immediately measured the thermal conductivity of mineral wool after soaking the material, which was followed by subsequent measurements taken at different time intervals while the mineral wool dried. The results showed that the moisture content and redrying of the mineral wool have an insignificant effect on the thermal conductivity of the material [21]. The research carried out by Gur'ev and Khainer on the thermal conductivity of fibrous materials showed that thermal conductivity is dependent on the moisture content of the material [22]. Abdou and Budaiwi analyzed materials of three different densities, particularly the glass fiber; subsequently, they compared the change in thermal conductivity with a measured change in the water content of the material. It was noted that materials that have a higher initial thermal conductivity and higher initial water content show a larger change in thermal conductivity with a change in the water content [23]. The numerical simulation of fibrous insulation materials facilitated Jintu's deduction that the three most important factors affecting the thermal conductivity are the initial moisture content, thickness of fiber insulation layer, and the ambient temperature [24]. D'Alessandro et al. placed thermal insulation of materials such as mineral wool and polyurethane foam in the climate room under relative humidity and tested the thermal conductivity of samples by using a hot disc apparatus to assess the effect of water content and the effect of different materials [25].

In summation, the moisture content has a significant impact on the thermal conductivity of thermal insulation materials. If a thermal insulation material absorbs water from its environment, its moisture content will change, which will lead to a significant difference between its actual thermal conductivity and that provided by manufacturers. Although the research on the performance of thermal insulation materials has been carried out extensively, thus far, the research on the water absorption characteristics and the thermal insulation performance after the successful absorption of water by thermal insulation materials is relatively scarce. Moreover, the tunnels in cold regions experience harsh conditions wherein the temperature differences between the day and night cycles in the tunnel portal section are substantial. At night, the temperature is as low as −20°C. Under these conditions, the water absorbed into the pore structure of the insulation material would easily be converted into ice. The freeze-thaw cycle would deteriorate the performance of the water-containing insulation material. Therefore, it is of great significance to study the water absorption and thermal insulation properties of thermal insulation materials used in the tunnels of cold regions. These properties are crucial for material manufacturers, building owners, and designers when selecting suitable insulating materials and correctly predicting the insulation performance of insulation materials and the antifreeze effect of tunnels.

In this study, the water absorption and the thermal conductivities of polyurethane and polyphenolic insulation boards were investigated under freeze-thaw conditions. An indoor water absorption test was conducted by placing the two materials in a temperature- and humidity-controlled box. To simulate the freeze-thaw cycle that is representative of the environment of cold-region tunnels, both insulation materials were subjected to a freeze-thaw cycle test after the sample had been saturated. Finally, the microstructures of the thermal insulation materials were examined using by a scanning electron microscope.

2. Materials and Methods

2.1. Material Selection and Material Properties. A polyphenolic insulation board and rigid polyurethane insulation board were selected as the test materials because they are commonly used in the lining of tunnels in the cold regions of China [26, 27]. The basic performance indicators of the materials are shown in Table 1. The sample size was determined to be 100 mm × 100 mm × 50 mm, as shown in Figure 1.

2.2. Test Process

2.2.1. Moisture Absorption Test. The samples were dried in an oven at about 60°C, until the mass reached a stable state. Subsequently the samples were cooled to room temperature in a drying cylinder. Subsequently, the samples were placed in sealed bags to mitigate the influence of air humidity on the moisture content of the samples. Before starting the moisture absorption test, the temperature of the constant temperature and humidity chamber was adjusted to 20°C. Then, the dried samples were placed in the moisture absorption device. After a period of moisture absorption, the mass of the sample was measured and recorded until the sample of the insulation material reached a stable moisture absorption state. The moisture absorption device used in this test is shown in Figure 2. Also, some technical parameters are shown in Table 2.

2.2.2. Freeze-Thaw Cycle Test. To simulate the repeated freeze-thaw cyclical process that occurs when thermal insulation materials are placed in cold-region tunnels, the samples were subjected to a moisture absorption freeze-thaw cycle test. The temperature of the low-temperature test box was adjusted in advance to −20°C. First, the absorption test process was repeated to ensure that the sample was saturated. Subsequently, when the samples attain saturation in the moisture absorption, they are stored in sealed bags. Then, they are placed in the low-temperature test box to freeze for 12 h, following which they are placed in the temperature- and humidity-controlled chamber to absorb moisture for 12 h at a temperature of 20°C and relative humidity of 95%. The abovementioned steps were repeated to complete the moisture absorption freeze-thaw cycle. After every five freeze-thaw cycle, the water absorption and thermal conductivity of the thermal insulation material was tested. The high and low temperature test chamber used in this

Table 1: Basic performance indicators of insulation materials.

Material types	Thermal conductivity (W/(m·K))	Density (kg/m^3)	Compressive strength (kPa)	Fireproof performance (grade)	Volumetric water absorption (%)	Temperature range (°C)
Polyphenolic	0.022~0.035	25~60	≥100	B1	≤6.5	−196~150
Polyurethane	0.022~0.030	25~80	≥150	B2	≤2	−50~100

Note: B1and B2 are the combustion performance grades of thermal insulation materials.

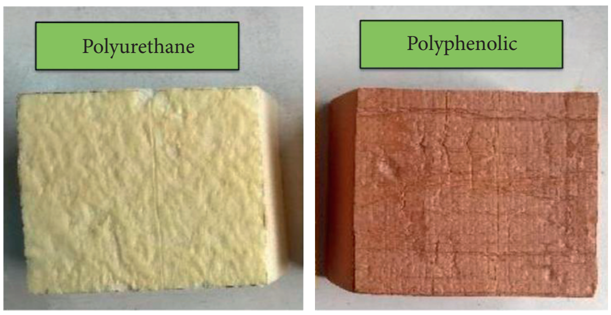

Figure 1: Insulation material samples.

Figure 2: Temperature- and humidity-controlled box.

Table 2: Some parameters of the constant temperature and humidity box.

Index	Parameter
Temperature range	0~60°C
Temperature fluctuation	±1°C
Temperature resolution	0.1°C
Relative humidity	45% RH~99% RH
Humidity error	<6% RH
Size	500 mm × 500 mm × 750 mm

Note: relative humidity is the ratio of absolute humidity in air to saturated absolute humidity at the same temperature.

experiment has been shown in Figure 3; furthermore, the sample was frozen, as shown in Figure 4.

2.3. Thermal Conductivity Test. The thermal conductivity test in this experiment is based on the Transient Plane Source (TPS) method and uses a Hot Disk-2500s Thermal Conductivity Meter, as shown in Figure 5. The Hot Disk Thermal Conductivity Meter consists of a test probe, thermal constant analyzer, and computer. The test probe is composed of a conductive nickel foil wire to form a double spiral shape. During the test, the probe is placed in the middle of the two samples of

Figure 3: High and low temperature test chamber.

Figure 4: Sample freezing.

the insulation material to form a sandwich structure. The probe has two components, namely, a heating source and a temperature sensor.

3. Results and Discussion

3.1. Water Absorption of Insulation Materials. From Figure 6, it can be seen that the water content of thermal insulation materials under 35% RH, 65% RH, and 95% RH has a similar relationship with time. The hygroscopic curve is relatively smooth and can be roughly divided into three stages: a rapid hygroscopic stage, stable hygroscopic stage, and saturated hygroscopic stage. Further, the relative humidity has been observed to be directly proportional to the saturated moisture absorption rate, moisture absorption, and time required to reach the equilibrium moisture content. Under the condition of 35% relative humidity (RH), the polyurethane thermal insulation material reached the equilibrium

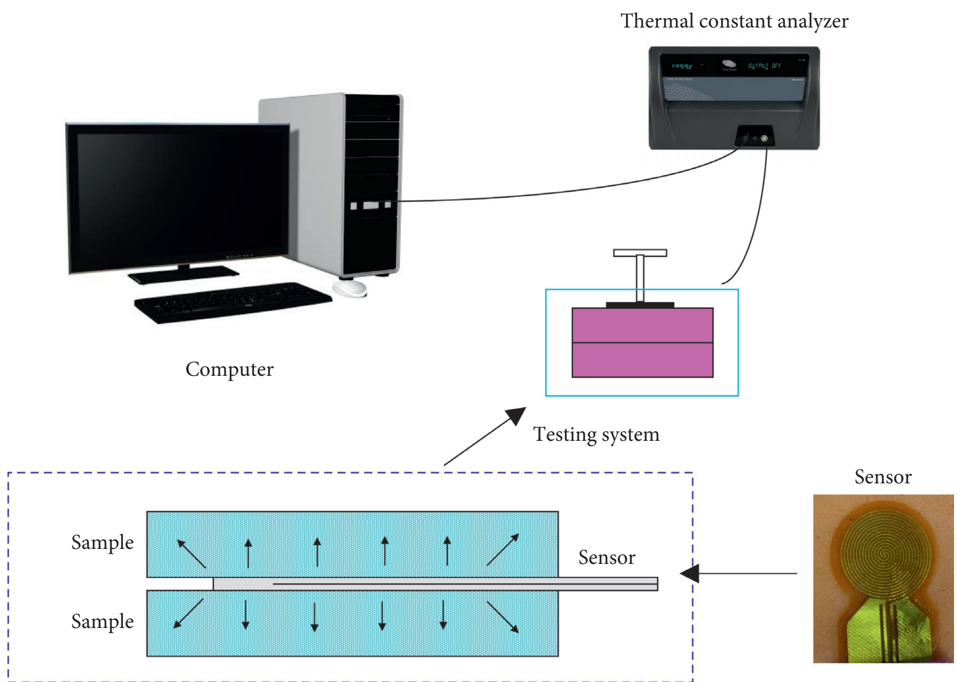

Figure 5: Thermal conductivity measuring device used in this study.

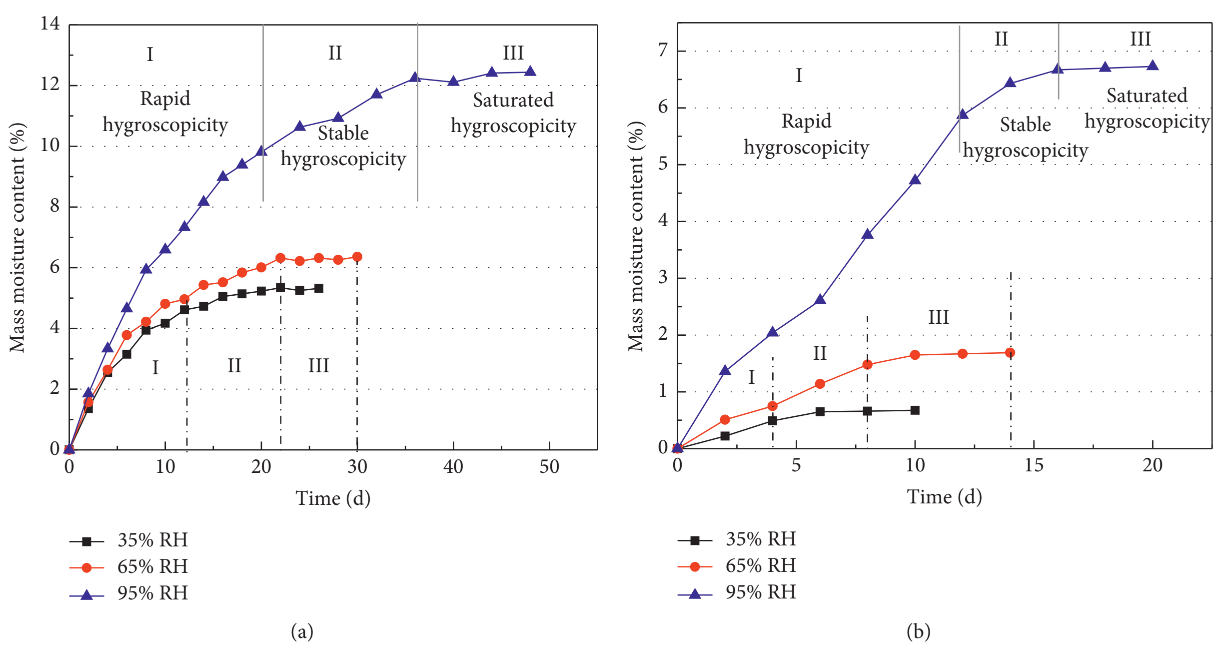

Figure 6: Relationship of the moisture content with respect to the mass percentage (%) and time. (a) Polyphenolic (b) Polyurethane.

moisture content of 0.65% after 6 d; whereas the polyphenolic thermal insulation material reached the equilibrium moisture content of 5.34% after 22 d. Under the condition of 65% RH, the polyurethane thermal insulation material reached the equilibrium moisture content state after 10 d wherein the equilibrium moisture content was 1.65, whereas the polyphenolic thermal insulation material reached the equilibrium state after 22 d with the equilibrium moisture content of approximately 6.32%. At 95% RH, the polyurethane material reached the equilibrium state of moisture absorption after 16 d, wherein the equilibrium moisture content was 6.74%. While the polyphenolic insulation material reached the equilibrium state after 36 d, the equilibrium moisture content was approximately 12.24%. Based on the abovementioned results, it can be concluded that there is a significant difference in the hygroscopic properties of the polyphenolic and polyurethane insulation materials. The equilibrium hygroscopic capacity of the polyphenolic insulation material is significantly greater than that of the polyurethane insulation material. The hygroscopic rate of the polyurethane insulation material is low at low humidity, which is related to the hydrophobic property of the material.

3.2. Effect of Freeze-Thaw Cycles on Water Absorption and Thermal Conductivity

3.2.1. Water Absorption. The effect of the number of freeze-thaw cycles on the water absorption in insulation materials is shown in Figure 7. It can be seen in this figure that, with an increase in the number of freeze-thaw cycles, the mass of water absorbed increases in an approximately linearly manner for both the insulation materials. The fitting formula for the change in water absorption of the polyphenolic insulation material with the number of freeze-thaw cycles is as follows:

$$\omega = 11.855 + 0.986N, \tag{1}$$

where N is the number of cycles. The fitting formula of the water absorption of the polyurethane material with the number of freeze-thaw cycles is as follows:

$$\omega = 6.671 + 0.0225N, \tag{2}$$

where N is, again, the number of cycles. It can be seen from Figure 8 that the moisture content of the polyurethane material changes insignificantly as compared to that of the polyphenolic material. In the absence of the freeze-thaw cycle, the water absorption rate of the polyphenolic insulation material sample was 12.8% in the highly humid environment, whereas that of the polyurethane insulation material sample was only 6.74%. The initial water absorption rates of both insulation materials were observed to be low in the humid environment. With an increase in the number of freeze-thaw cycles, the water absorption of the sample also increased to an extent. After 25 cycles of the freeze-thaw test, the water absorption reached 33.79%, which was 1.6 times higher than the initial water absorption. After 50 cycles of the freeze-thaw test, the water absorption reached 60.14%, which was 3.7 times higher than the initial water absorption. The water absorption of polyphenolic insulation materials was observed to be affected by the freeze-thaw cycle. After 50 cycles of the freeze-thaw test, the water absorption of polyurethane insulation materials reached 7.85%, which was 16% higher than the initial water absorption. This shows that the water absorption rate of the polyurethane insulation material is less affected by the freeze-thaw cycle in a humid environment.

3.2.2. Thermal Conductivity. The thermal conductivity of the two insulation materials measured against the number of freeze-thaw cycles is shown in Figure 9. It can be seen in this figure that, with an increase in the number of freeze-thaw cycles, the thermal conductivities of the two insulation materials also increases in a linearly manner. The fitting formula of the thermal conductivity of the polyphenolic sample with the number of freeze-thaw cycles is as follows:

$$\lambda_e = 0.0279 + 2.7746 \times 10^{-4}N, \tag{3}$$

where N is the number of freeze-thaw cycles completed. The fitting formula for the thermal conductivity of the polyurethane sample with the number of freeze-thaw cycles is as follows:

$$\lambda_e = 0.02782 + 1.0691 \times 10^{-5}N, \tag{4}$$

where N is the number of freeze-thaw cycles completed. It can be seen from Figure 8 that the change in the thermal conductivity of the polyphenolic thermal insulation material is more significant than that of the polyurethane insulation material. The thermal conductivity of the polyphenolic thermal insulation material without freeze-thawing was observed to be 0.0305 W/(m·K). After 50 cycles of freeze-thawing, the thermal conductivity reaches 0.0442 W/(m·K), which is nearly 50% higher than the initial thermal conductivity. The thermal conductivity of the polyurethane thermal insulation material without freeze-thawing was 0.0278 W/(m·K). However, due to its low moisture absorption, after 50 freeze-thaw cycles, the thermal conductivity reached 0.02833 W/(m·K). This increase in the thermal conductivity was not more than 2% of the original value. The thermal conductivity of the polyurethane insulation material, which has a low rate of water absorption, increased slightly with an increase in the number of freeze-thaw cycles. Furthermore, it can be considered that the thermal conductivity of polyurethane insulation materials is not affected by freeze-thaw cycles.

3.3. Thermal Conductivity of Insulation Materials at Room Temperature. The thermal conductivities of the two insulation materials measured against the moisture content as mass percentages are shown in Figure 10. The thermal conductivity of the polyphenolic and polyurethane insulation materials increased almost linearly with an increase in the water content. For the polyphenolic insulation material, when the moisture content of the sample reached 78.78%, the thermal conductivity was 0.03742 W/(m·K); this value was 26.8% higher than that of the dry material. For polyurethane insulation materials, when the mass moisture content of the sample reached 14.06%, the thermal conductivity was 0.02986 W/(m·K); this value was 14.4% higher than that of the dry sample. The thermal conductivity of polyurethane and polyphenolic is similar when the moisture content is 0. However, the water absorption rate of the polyurethane material is lower, which means that the thermal conductivity of polyurethane is less than that of polyphenolic. Therefore, from the perspective of thermal conductivity, polyurethane insulating materials are better.

The fitting formula of the relationship between the thermal conductivity and the moisture content of polyphenolic materials is

$$\lambda_e = 0.0295 + 9.633 \times 10^{-3}\omega, \tag{5}$$

where λ_e is the thermal conductivity and ω is the moisture content. The fitting formula of the relationship between the

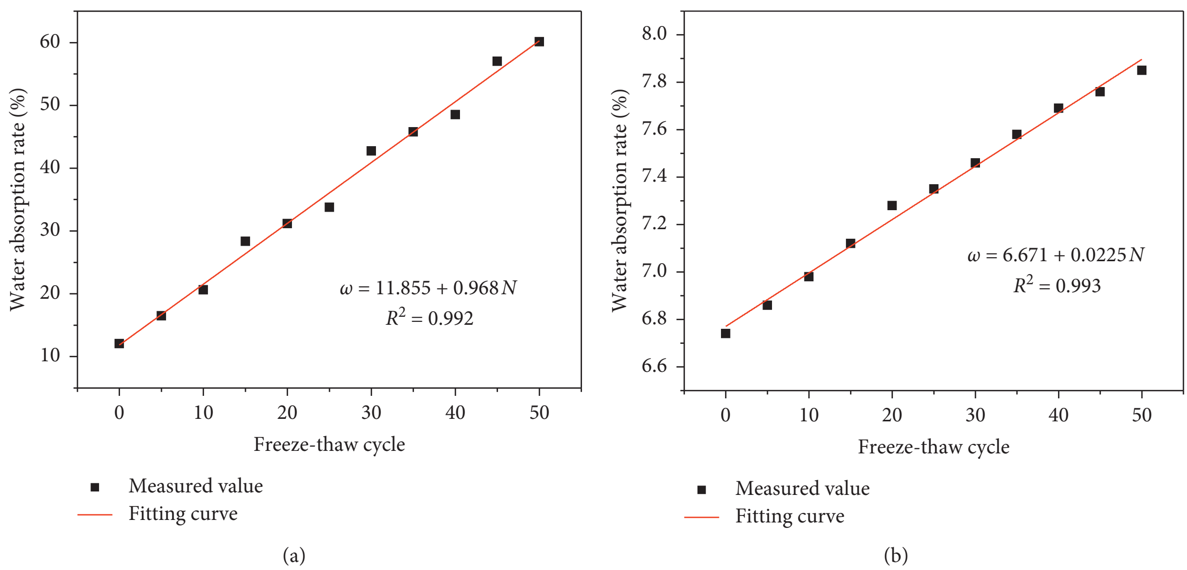

Figure 7: Effect of freeze-thaw cycles on water absorption of insulation materials. (a) Polyphenolic (b) Polyurethane.

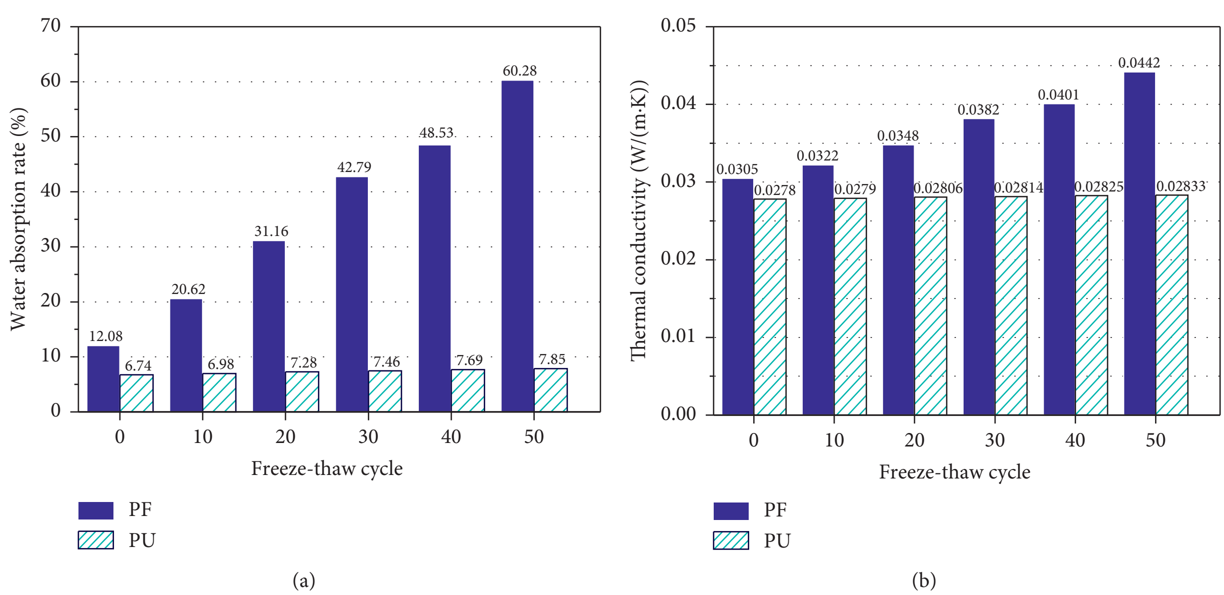

Figure 8: Changes in water absorption and thermal conductivity of insulation materials under freeze-thaw cycles. (a) Water absorption rate. (b) Thermal conductivity.

thermal conductivity and the moisture content of the polyurethane material is

$$\lambda_e = 0.0261 + 2.5485 \times 10^{-2}\omega, \quad (6)$$

where λ_e is the thermal conductivity and ω is the moisture content.

3.4. Relationship between Thermal Conductivity and Ice Content after Freezing. The relationships between the thermal conductivities and the ice contents of the two insulation materials are shown in Figure 11. In general, once the water inside the insulation material was frozen, its thermal conductivity was observed to change dramatically. This was mainly because of the thermal conductivity of the dry thermal insulation materials being far less than that of ice. With an increase in the ice content, the thermal conductivity of the two kinds of thermal insulation materials increased gradually. Furthermore, it was observed that the rate of thermal conductivity increases more significantly than that observed before freezing. The change in the thermal conductivity was more sensitive after the insulation material had been frozen at low temperatures. The thermal conductivity of frozen samples was generally larger than that observed before freezing. Only when the ice content in the materials was 0, the two values were close; this shows that freezing has an insignificant effect on the thermal conductivities of dry insulation materials. The thermal

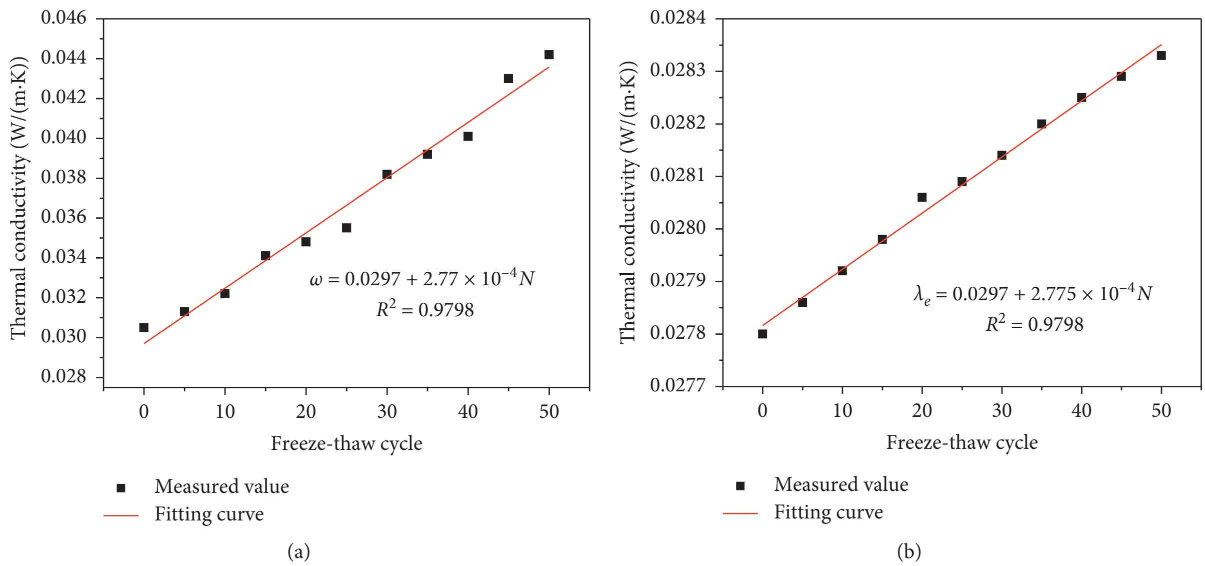

Figure 9: Effect of freeze-thaw cycles on thermal conductivity of thermal insulation materials. (a) Polyphenolic. (b) Polyurethane.

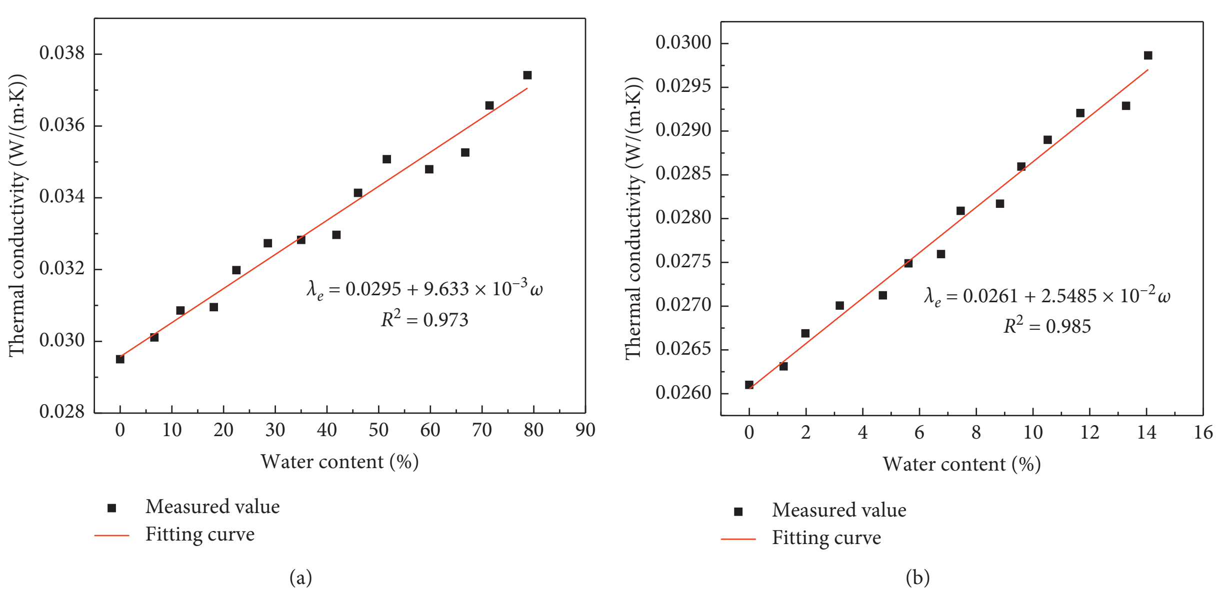

Figure 10: Relationships between the thermal conductivity and water content of polyphenolic and polyurethane insulation boards at room temperature. (a) Polyphenolic. (b) Polyurethane.

conductivity of ice has been established to be 2.3 W/(m·K), which is about 4 times than that of water (0.581 W/(m·K)). When the water inside the thermal insulation material is converted into ice, at freezing temperatures, the thermal conductivity is bound to increase. Therefore, the thermal conductivities of the two insulation materials gradually increased with an increase in the ice content. In particular, the thermal conductivity of the polyphenolic insulation material increases in a parabolic manner, as can be seen in Figure 11(a), with an increase in the ice content. As shown in Figure 11(b), for polyurethane thermal insulation materials, the curve of the thermal conductivity changes with the ice content. This was divided into two stages; the first stage was the thermal conductivity fluctuation stage, and the corresponding change in the range of the ice content was from 0% to 5%; herein, it should be noted that the thermal conductivity fluctuates up and down. The second stage was the stable growth stage of thermal conductivity, with the corresponding variation in the ice content in the range of 5% to 14%, and the thermal conductivity increased linearly with the ice content. When the ice content was 14.11%, the thermal conductivity increased by 20.6% as compared with that when it was dry.

3.5. Analysis of the Degradation Mechanism of Water-Containing Insulation Materials. It can be seen from Figure 12(a) that most of the original pore structures of the polyurethane thermal insulation material exhibit a closed-cell pore structure, with a small number of natural open-cell

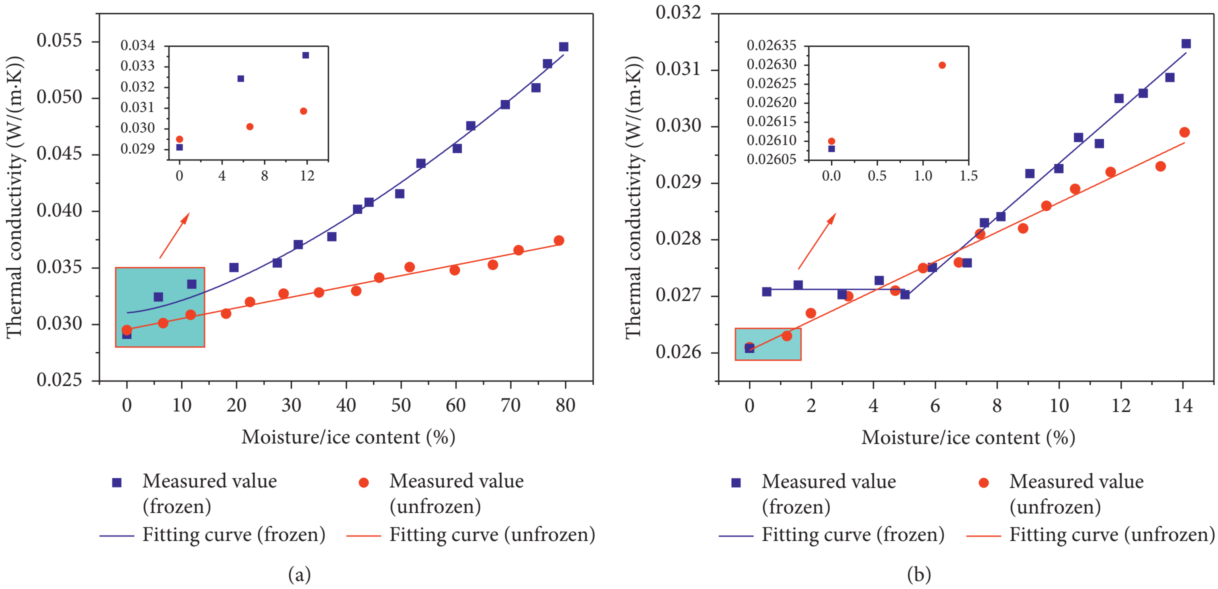

FIGURE 11: Thermal conductivity of the insulation material before and after freezing. (a) Polyphenolic. (b) Polyurethane.

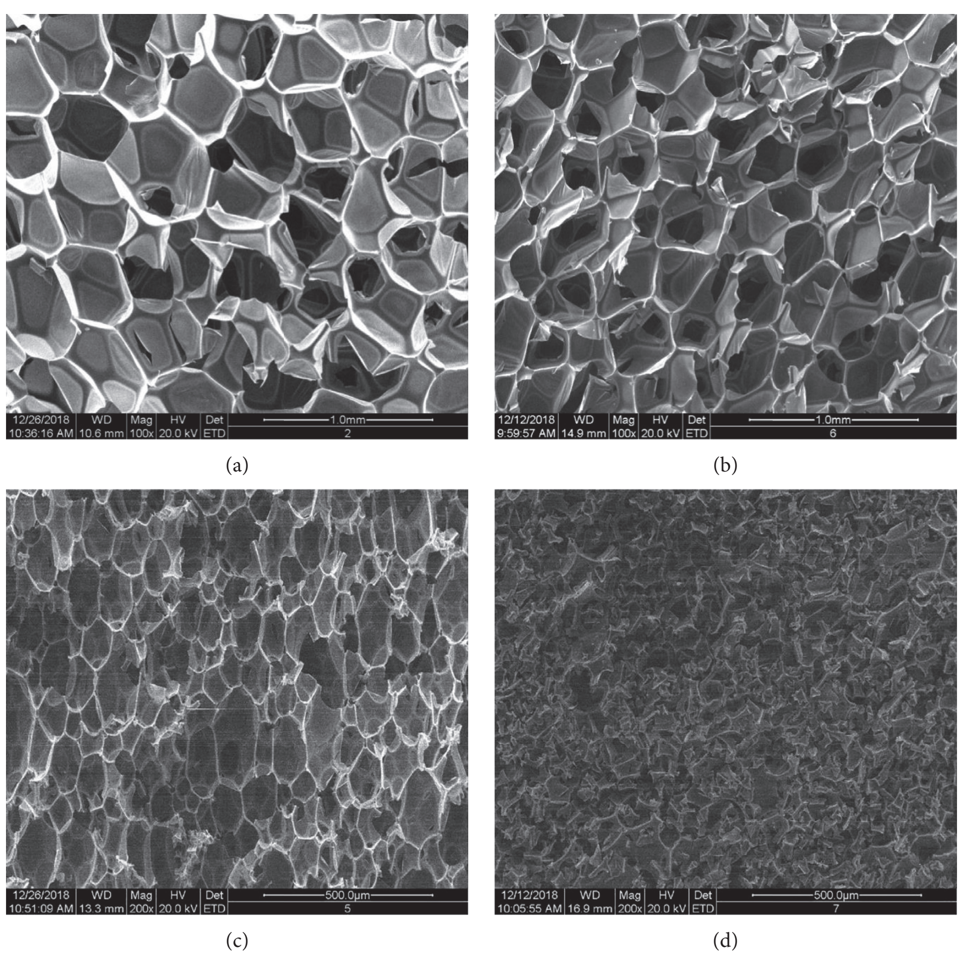

FIGURE 12: Micropore structures of the thermal insulation materials. (a) Polyurethane insulation that is not freeze-thawed. (b) Polyurethane insulation freeze-thawed 50 times. (c) Polyphenolic insulation that is not freeze-thawed. (d) Polyphenolic insulation freeze-thawed 50 times.

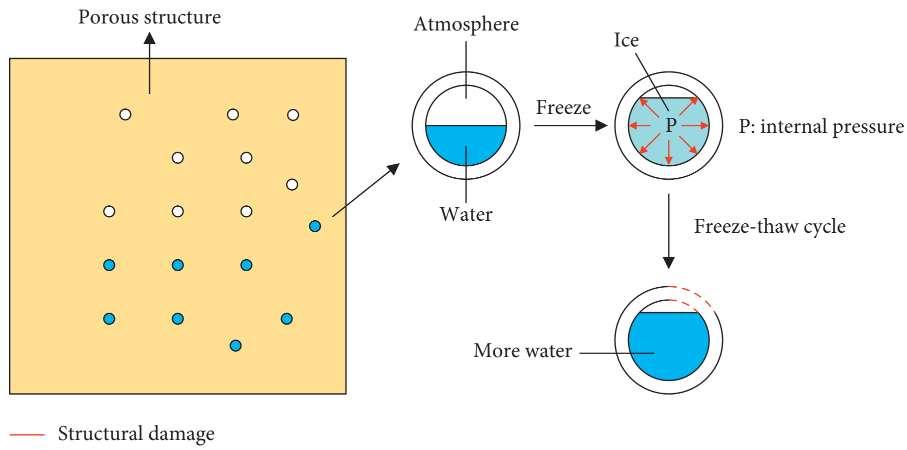

Figure 13: Deterioration mechanism of the thermal insulation material under the freeze-thaw cycle.

structures. The internal skeleton structure before the freeze-thaw test was observed to be primarily intact with a few local fractures. It can be observed from Figure 12(b) that, after 50 freeze-thaw cycles, the number of open pores in the polyurethane insulation material gradually increases, and the number of closed pores decreases. It can be seen from Figure 12(c) that the micropore structure of the polyphenolic thermal insulation material constitutes a small and dense honeycomb shape before being subjected to the freeze-thaw test. A small amount of skeleton fractures were observed to form due to the inevitable defects of the production process. After 50 cycles of the freeze-thaw test, the skeleton structure was seriously damaged with almost no skeletal shape, as shown in Figure 12(d). Furthermore, the pore structure damage to the polyphenolic insulation material was more serious than the damage to the polyurethane insulation material. Under the freeze-thaw cycle, the deterioration of the thermal insulation performance of thermal insulation materials was mainly manifested on the macroscopic scale by the increase in the thermal conductivity, which was caused due to the continuous increase in water absorption. At a microscopic scale, the internal pore structure of the thermal insulation materials was damaged. With an increase in the number of freeze-thaw cycles, the closed pores gradually changed into open pores, and a fracture of the skeleton structure occurred. This rendered it easier for water to enter into the sample; furthermore, at a macroscopic level, it resulted in an increase in the absorption of water.

The degradation mechanism of the insulation materials under the action of the freeze-thaw cycles is shown in Figure 13. The thermal insulation material exhibited a loose pore structure that was dependent on the relative humidity in the environment, such that the water absorption performance was directly proportional to the relative humidity. During the freeze-thaw cycle, the volume of the water in the liquid or solid phase was observed to change continuously. This led to the generation of an internal pressure that caused the bubble wall to break along with the skeletal structure of the insulation material, which, in turn, led to more water entering the insulation material. With an increase in the number of freeze-thaw cycles, an increase in the damage to the insulation material structure was observed. Furthermore, this caused more water to infiltrate the sample, which increased the water absorption of the insulation material. Moreover, the destruction of the pore structure of the thermal insulation material and the increase in the water absorption rate were observed to enhance one another, exacerbating the deterioration process of the material. Because the thermal conductivities of water and ice are 0.581 W/(m·K) and 2.3 W/(m·K), respectively, which are significantly larger than that of air (about 0.023 W/(m·K)), the thermal conductivity of the insulation material also increases with the number of freeze-thaw cycles.

4. Conclusions

In this study, the water absorption and thermal insulation properties of insulation materials used in cold region tunnels under freeze-thaw conditions were studied. The results show that

(1) Under the freeze-thaw cycle, the water absorption and thermal conductivities of the polyphenolic and polyurethane insulation boards were observed to increase linearly and steadily with the number of freeze-thaw cycles. After 50 freeze-thaw cycles, the water absorption of the polyphenolic insulation increased by nearly 3.7 times, and the thermal conductivity increased by 50%. Under the same conditions, after 50 freeze-thaw cycles, the thermal conductivity of the polyurethane material increased by no more than 2%.

(2) At room temperature, the thermal conductivity of the two thermal insulation materials increased linearly with the moisture content.

(3) For the polyphenolic insulation material, the curve of the thermal conductivity with the change in the ice content was shaped like a parabola. For polyurethane thermal insulation materials, the change in the thermal conductivity with the ice content was

divided into two stages, namely, ice contents of 0–5% and >5%. The thermal conductivity fluctuated when the ice content was between 0 and 5%; furthermore, the thermal conductivity increased steadily in a linear trend when the ice content was more than 5%.

(4) Under the action of the freeze-thaw cycle, the closed-cell microstructure of the thermal insulation material was damaged, with the structural damage to polyphenolic insulation being more severe.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was supported by the National Natural Science Fund of China (Grant no. 51378071) and Natural Science Foundation of Shaanxi Province of China (Grant no.2130-2116-0351). The authors are grateful to the researchers for their support in the experimental study.

References

[1] Y. Lai, W. Hui, L. Songyu, and D. Xuejun, "Analytical viscoelastic solution for frost force in cold-region tunnels," *Cold Regions Science and Technology*, vol. 31, no. 3, pp. 227–234, 2000.

[2] Y. Lai, S. Liu, Z. Wu, and W. Yu, "Approximate analytical solution for temperature fields in cold regions circular tunnels," *Cold Regions Science and Technology*, vol. 34, pp. 43–49, 2002.

[3] L. Liu, Z. Li, X. Liu, and Y. Li, "Frost front research of a cold-region tunnel considering ventilation based on a physical model test," *Tunnelling and Underground Space Technology*, vol. 77, pp. 261–279, 2018.

[4] S. Zhang, Y. Lai, X. Zhang, Y. Pu, and W. Yu, "Study on the damage propagation of surrounding rock from a cold-region tunnel under freeze-thaw cycle condition," *Tunnelling and Underground Space Technology*, vol. 19, no. 3, pp. 295–302, 2004.

[5] Z. Lv, C. Xia, Y. Wang, and J. Luo, "Analytical elasto-plastic solution of frost heaving force in cold region tunnels considering transversely isotropic frost heave of surrounding rock," *Cold Regions Science and Technology*, vol. 163, pp. 87–97, 2019.

[6] X. Zhang, Y. Lai, W. Yu, and Y. Wu, "Forecast analysis for the re-frozen of feng Huoshan permafrost tunnel on Qing-Zang railway," *Tunnelling and Underground Space Technology*, vol. 19, no. 1, pp. 45–56, 2004.

[7] L. Duan, Y. Zhang, and J. Lai, "Influence of ground temperature on shotcrete–to–rock adhesion in tunnels," *Advances in Materials Science and Engineering*, vol. 2019, Article ID 8709087, 16 pages, 2019.

[8] J. Lai, X. Wang, J. Qiu et al., "A state-of-the-art review of sustainable energy based freeze proof technology for cold-region tunnels in China," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3554–3569, 2018.

[9] J. X. Liu, Q. J. Hu, Y. T. Liu, and Z. W. Long, "Simulation and analysis of frost heave force for tunnel lining," *Applied Mechanics and Materials*, vol. 204–208, pp. 1374–1379, 2012.

[10] Y.-M. Lai, Z. Wu, Y. Zhu, and L. Zhu, "Nonlinear analysis for the coupled problem of temperature and seepage fields in cold regions tunnels," *Cold Regions Science and Technology*, vol. 29, no. 1, pp. 89–96, 1999.

[11] T. Wang, G. Zhou, J. Wang, and X. Zhao, "Stochastic analysis for the uncertain temperature field of tunnel in cold regions," *Tunnelling and Underground Space Technology*, vol. 59, pp. 7–15, 2016.

[12] P. Qi, J. Zhang, and Z. Mei, "Study on the range of freeze–thaw of surrounding rock from a cold–region tunnel and the effects of insulation material," *Advanced Materials Research*, vol. 399–401, pp. 2222–2225, 2012.

[13] Q. Ma, X. Luo, Y. Lai, F. Niu, and J. Gao, "Numerical investigation on thermal insulation layer of a tunnel in seasonally frozen regions," *Applied Thermal Engineering*, vol. 138, pp. 280–291, 2018.

[14] X. Tan, W. Chen, D. Yang et al., "Study on the influence of airflow on the temperature of the surrounding rock in a cold region tunnel and its application to insulation layer design," *Applied Thermal Engineering*, vol. 67, no. 1-2, pp. 320–334, 2014.

[15] S. Li, F. Niu, Y. Lai, W. Pei, and W. Yu, "Optimal design of thermal insulation layer of a tunnel in permafrost regions based on coupled heat-water simulation," *Applied Thermal Engineering*, vol. 110, pp. 1264–1273, 2017.

[16] W. Pei, W. Yu, S. Li, and J. Zhou, "A new method to model the thermal conductivity of soil-rock media in cold regions: an example from permafrost regions tunnel," *Cold Regions Science and Technology*, vol. 95, pp. 11–18, 2013.

[17] M. S. Camino–Olea, A. Cabeza–Prieto, and A. Llorente–Alvarez, "Brick walls of buildings of the historical heritage. Comparative analysis of the thermal conductivity in dry and saturated state," *IOP Conference Series: Materials Science and Engineering*, vol. 471, Article ID 082059, 2019.

[18] M. Khoukhi, "The combined effect of heat and moisture transfer dependent thermal conductivity of polystyrene insulation material: impact on building energy performance," *Energy and Buildings*, vol. 169, pp. 228–235, 2018.

[19] M. Jerman and R. Černý, "Effect of moisture content on heat and moisture transport and storage properties of thermal insulation materials," *Energy and Buildings*, vol. 53, pp. 39–46, 2012.

[20] B. Abu-Jdayil, A.-H. Mourad, W. Hittini, M. Hassan, and S. Hameedi, "Traditional, state-of-the-art and renewable thermal building insulation materials: an overview," *Construction and Building Materials*, vol. 214, pp. 709–735, 2019.

[21] B. Loboda and F. Szurman, "Thermal conductivity coefficient research on mineral wool after partial immersion in water and drying to constant mass," *IOP Conference Series: Materials Science and Engineering*, vol. 471, Article ID 022022, 2019.

[22] V. V. Gur'ev and S. P. Khainer, "Correlation of structure and thermal conductivity of highly disperse porous-fiber materials under variations of temperature and moisture," *Glass and Ceramics*, vol. 56, pp. 11-12, 1999.

[23] A. Abdou and I. Budaiwi, "The variation of thermal conductivity of fibrous insulation materials under different levels of moisture content," *Construction and Building Materials*, vol. 43, pp. 533–544, 2013.

[24] J. Fan and X. Wen, "Modeling heat and moisture transfer through fibrous insulation with phase change and mobile condensates," *International Journal of Heat and Mass Transfer*, vol. 45, no. 19, pp. 4045–4055, 2002.

[25] F. D'Alessandro, G. Baldinelli, F. Bianchi, S. Sambuco, and A. Rufini, "Experimental assessment of the water content influence on thermo-acoustic performance of building insulation materials," *Construction and Building Materials*, vol. 158, pp. 264–274, 2018.
[26] Y. B. Luo, J. X. Chen, and H. L. Chao, "Division of frost damage grades and its prevention measures in tunnel," *Advanced Materials Research*, vol. 535–537, pp. 1977–1984, 2012.
[27] P. Zhao, J. Chen, and Y. Luo, "Investigation of the insulation effect of thermal insulation layer in the seasonally frozen region tunnel: a case study in the zuomutai tunnel, China," *Advances in Civil Engineering*, vol. 2019, Article ID 4978359, 14 pages, 2019.